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Seismic velocity gradient stratification of the mantle at Ukrainian Shield

***Y. I. Dubovenko**, **L. A. Shumlianska** *(Institute of Geophysics by S. I. Subbotin NAS of Ukraine)*, **M. P. Kuzminets** *(National Transport University)*

SUMMARY

The purpose of the thesis is to use gradient analysis to form a new high-speed seismic-tomographic model (set of new boundaries) of the inhomogeneous mantle. We use the Taylor approximation on the P-waves first arrivals from earthquakes of magnitude $M \geq 4.5$, the periods of which are in the range of $T = 5$ sec. At these conditions for the IASP91 velocity model at depths H = 50-650 km the wavelength λ varies within 40–50 km, ranging our method resolution. Taking that in account, we have developed a new approach for the mantle boundaries definition based on the successive mean velocity derivatives calculations. Using it, we define the 1st and 2nd derivatives (velocity gradients) at different tectonic units of Ukrainian Shield.

Results of the approach application was the keyboard-alike patterns for real transforms along two conso¬lidated profiles. The 2.5D model of velocity gradients of P-waves within the upper mantle in the depth range of 50–700 km shows the quite different images. It results in the identification of a set of new velocity gradient boundaries.

Practical value of the initial qualitative interpretation is that these boundaries lay within three principal structural horizons of the upper mantle (under ~200–300 km, ~410–500 km, and ~600–650 km).

Introduction. A global seismology has achieved remarkable success in the mapping of disruptions in the mantle. Using various techniques of seismic *tomography*, the chemical anomalies and phase *transitions* in the upper and lower mantle have been studied. This direction of seismic was developed from the interpretation of 1D *velocity* models in the 1970-80s. The main *mantle zones* were identified; for example, Johnson (1969) examined 212 deep earthquakes and revealed global anomalies of v_p gradients at depths of 830, 1230, 1540, 1910, and 2370 km. He suggested that these anomalies are caused by changes in the composition and density of the mantle

This method of mantle heterogeneity mapping is used to determine the mantle boundaries under the Ukrainian Shield using the velocity mantle model (Geyko et al., 2006). The model consists of a set of 1D velocity curves obtained from the hodograph *inversion*, and a set of curves forms a *quasi* 3D velocity model. Each velocity curve characterizes a certain volume of the geological media with the certain velocity values at each point of the volume.

At Ukraine, the two types of seismic tomographic model was derived, one for the average model of the Earth's crust of Jeffreys-Bullen (Shumlianskaya, 2014), another for the *modified* model of the Earth's crust, obtained according to the DSS data (Kravtsov and Orlov, 1980). We use the second model, with the velocity structure of the Earth's crust close to the real *crust* image by DSS, because it allows us to specify the velocity distribution in the model of the upper mantle up to 200-350 km under different megablocks of the Ukrainian shield more *precisely*.

The purpose of the study is to use gradient analysis to form a new high-speed seismic-tomographic model (set of new boundaries) of the inhomogeneous mantle. This approach is justified for modeling the chemical and physical properties of the mantle. The simulation itself is a task for the following experiments.

The method and/or theory. The 1D velocity curves for the mantle of the Ukrainian shield are obtainned from the *inversion* of the hodographs of the refracted waves, which limits strictly the solutions obtained. The techniques for solution the inverse kinematic problems of seismic, including the Taylor approximation approach are based on laws of geometric seismic. This implies that the minimal size of truly distinguished features of mantle structure cannot be less than the Fresnel volume correlated with the wavelength.

Well-known speed models (PREM, AK135, and others) have the biggest differences in the upper section of the incision in the Earth's crust and adjacent mantle layer to the boundary of the Moho. For the principal purpose that stood before us, the choice of the general Earth velocity model does not make much difference. We took the IASP-91 as one of the most popular models in the literature. For different velocity models (such as IASP-91, PEM, Geyko model) the velocity curves in the mantle are almost identical in number values but different in the geometry of curves. To account for the continuity of *discontinuities* in terms of wavelength, the difference is only of ~5 km wavelength, while the step along the velocity curve in the initial model, i.e. before smoothing, equals 25 km, and after smoothing it is of 50 km. That is, for the physical plausibility of this method of velocity anomalies determination, the value of displacement about 5 km is not crucial.

Many methods of seismological tomography are based on the study of transverse waves. However, we chose the longitudinal waves to model the structure of the upper mantle. Determining the first introduction of transverse *S*-waves is a non-trivial task, therefore in practical seismology, the keen interpreter must apply several methods of analysis. In addition to the visual, they use the polarization method for confident selection, which allows tracking the movement of particles in 3-dimensional space, the wavelet analysis, and others. Moreover, when in mass processing, if in doubt, the introduction of the *S*-wave does *not indicate* in the seismic bulletins at all, so as not to waste the time. We use the truly available Seismological bulletin of the International Seismological Service with data for 1970-2012 to construct the appropriate hodographs. In the earthquake fixation report, the total number of *S*-wave entries is only 10-20% of the P-wave entries are fixed.

In addition, the territory of Ukraine is in the *low seismic* zone, so the amount of primary seismic material is extremely *insufficient* for the construction of hodographs, and the coverage of seismic stations is *poor*, their common location is *uneven*, which further aggravates the situation of the selection of primary seismic material. For comparison, now the network of seismic stations of the Institute of Geophysics (NAS of Ukraine) consist of **27** stations and 20 of them are located in the Carpathian region of Ukraine. The required number of seismic stations for the *optimal* network should be at least **137** stations, which should be located on a *uniform* grid throughout the territory of Ukraine. Thus, we choose the P-waves for the tomographic model because of the absence of *another* reliable source of primary seismic information within the area studied. If we set the problem of constructing the velocity model by the curves of the transverse S waves, then we will have a model with large *averaging* over the area of investigation, for example, only *one* reliable hodograph over the whole territory of Ukraine.

To construct the reliable hodographs using the Taylor *approximation*, data were used on the P-waves first *arrivals* from earthquakes traveltimes of magnitude $M \geq 4.5$, the periods of which are in the range of $T = 5 \div 10$ sec. The approximate wavelength of the disturbance is $\lambda = T{\cdot}v$, where v is the wave velocity; T is the period of the disturbance wave. For most adequate period $T = 5$ sec of the mantle velocities for the IASP91 model, the wavelength is shown in Figure 1. From Figure 1 it can be seen that at depths H = 50-650 km, the wavelength λ varies within 40–50 km. This is the range of our method resolution for the seismic tomography, including the Taylor approximation. Besides are given the 1st and 2nd derivatives for IASP91 velocity model that demonstrate the patterns for corresponding real hodograph transforms at different tectonic units of Ukrainian Shield, shown below.

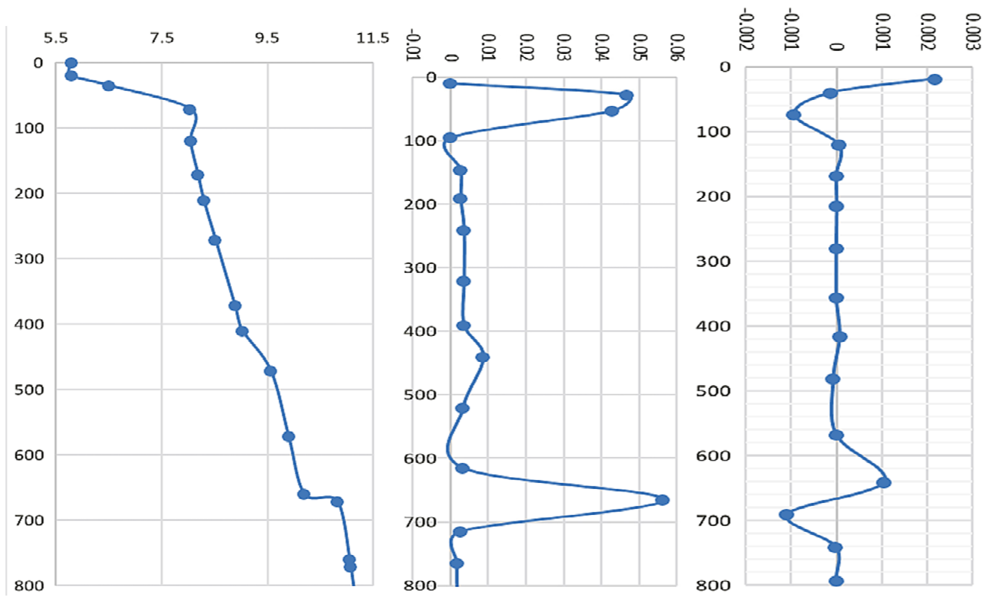

Figure 1. *IASP-91 model: mean P-waves velocity, its first and second derivative (seen left to right) vs depth H taken for a period of longitudinal waves T = 5 sec of distant earthquakes.*

Taking into account the above arguments, the boundaries of the mantle inhomogeneities along the gradient of the velocity curve v_p were determined in order to eliminate false anomalies and fluctuations of the velocity curves that occur when the hodograph is converted into a velocity curve. To this end, a smoothing procedure for the v_p curve was performed with a step proportional to the wavelength of 50 km. The obtained velocity gradient curves are then compared with hodographs of average velocities in order to isolate anomalies whose scale is not less than the wavelength.

The physical meaning of gradv_p gradient anomalies is as follows: to highlight the gradient anomalies of the v_p curve, we distinguish the sections with different velocity accelerations in certain layers of the upper mantle. Within each interval with the same acceleration value, we assume the presence of the mantle substance anomalies of the same nature. The singular points determined by the kinks of the

gradient curve are denoted as possible boundaries of additional inhomogeneities within the existing mantle zones. The elastic media must satisfy the strict ratio of the perturbation wavelength to the characteristic dimensions of the media inhomogeneities under the study. So, we examine the various conditions (Figures 2 and 3), taking into account that the Fresnel volume limitations (Kravtsov and Orlov, 1980).

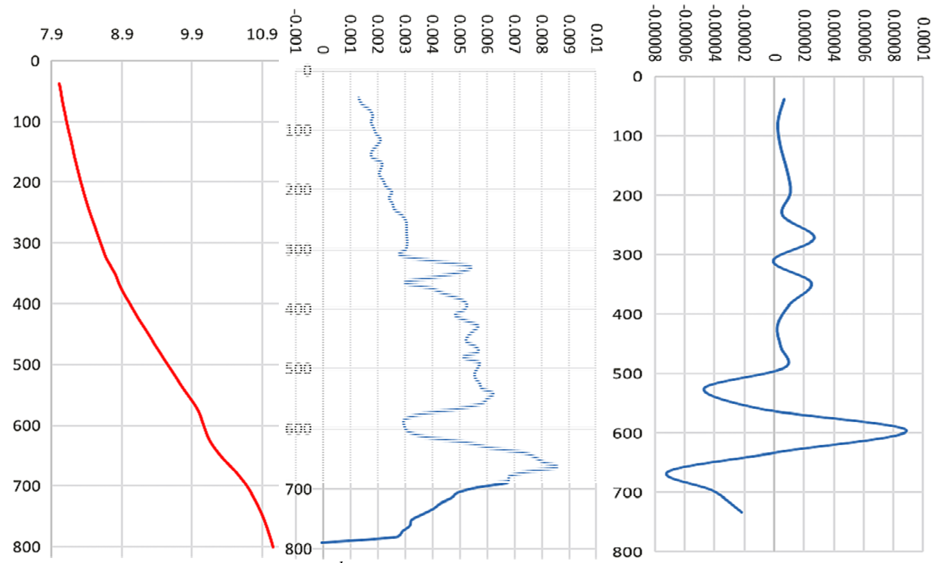

Figure 2. *Mean velocity, its 1st and 2nd derivatives at the averaging step of 40 km for tectonic units within Ukrainian Shield.*

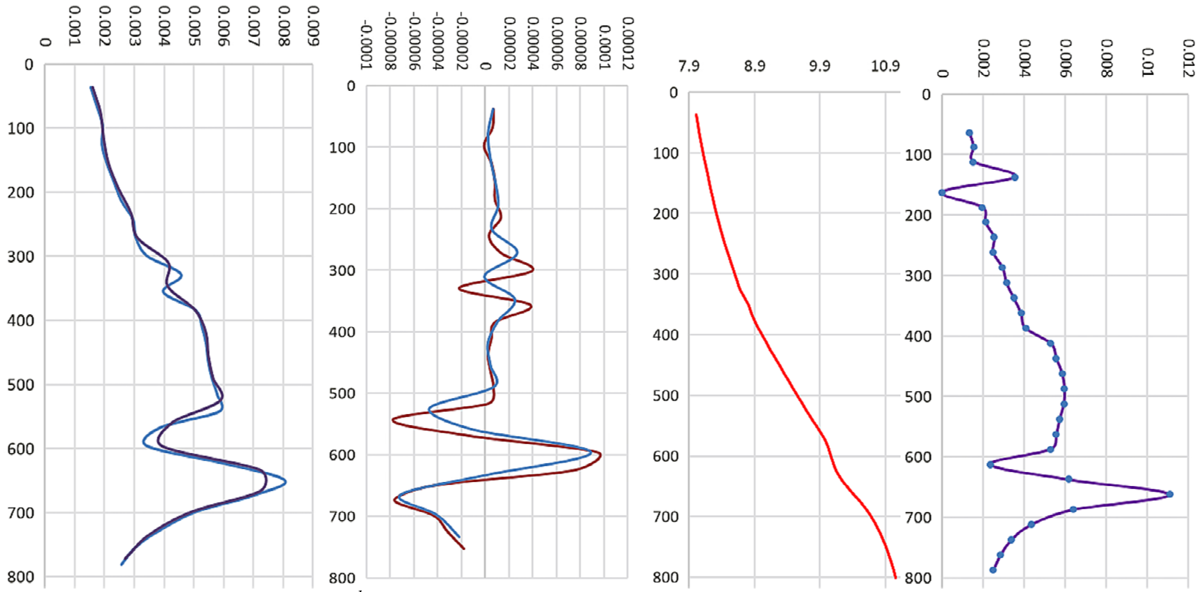

Figure 3. *Curves of 1st and 2nd derivatives of P-waves velocity at the averaging step of 30 (red) and 40 km (blue); mean velocity (red) and its 1st derivative at the averaging step of 25 km for Pryazovsky megablock of Ukrainian Shield.*

The results and discussion. With the technique mentioned above we received the layout of the new set of mantle inhomogeneities with respect to 1st and 2nd mean velocity derivatives (gradients) for the whole Ukrainian shield (Figure 4) along two almost parallel composite profiles. Analysis of the velocity gradients of *P*-waves in the upper mantle in the depth range of 50-650 km identifies the new velocity stratification. These boundaries lay within the framework of the three known structural horizons of the upper mantle (~200-300 km, ~410-500 km, ~600-650 km). Hardly ever, we can draw any clear conclusions about their geological nature before checking the stability and resolution of the proposed approach by other independent seismological methods, including methods of reflected waves, whose

resolution is independent of wavelengths. Another representation of mantle inhomogeneities distribution as smoothed vertical *in-depth distribution* for the same data along the profile mentioned is shown in Figure 5. It is useful for qualitative analysis of possible density gradients allocation.

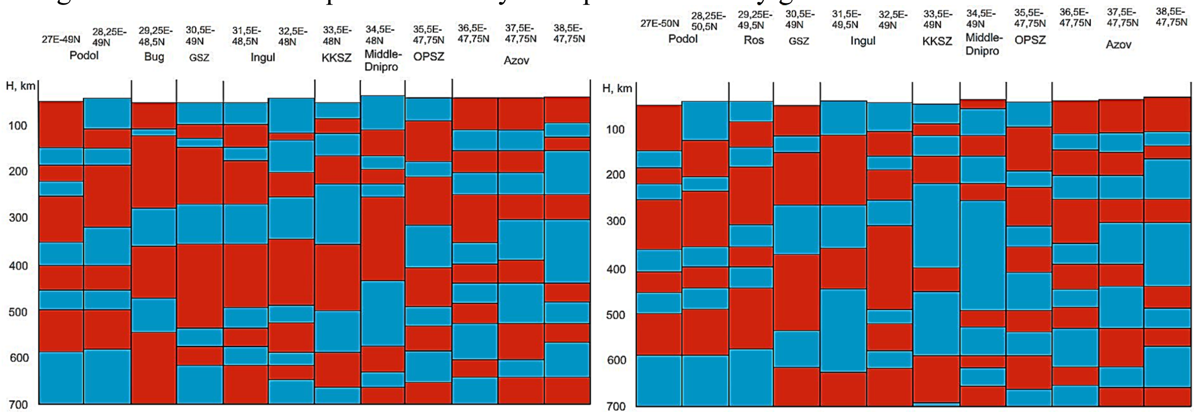

***Figure 4**. The layout of possible mantle irregularities with min (blue) and max (red) anomalies of gradv_p constructed from curve gradgradv_p.*

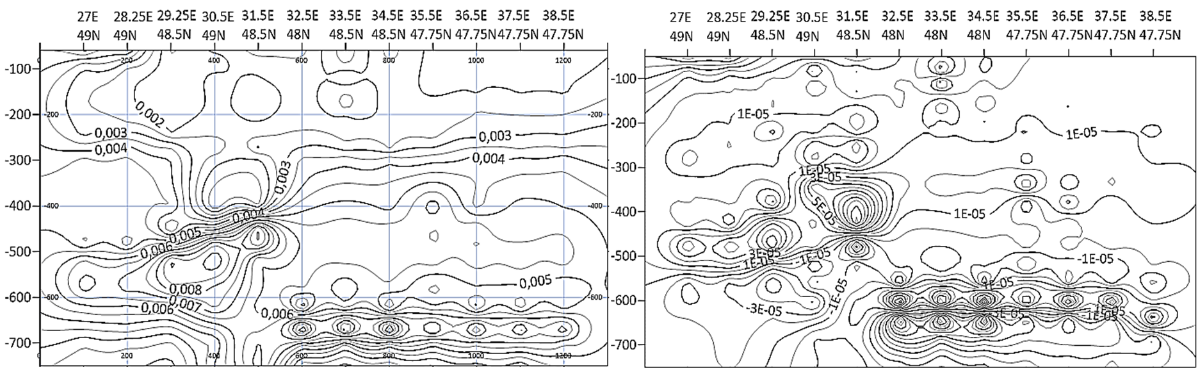

***Figure 5.** The layout of in-depth distribution for 1st (gradv_p, left) and 2nd (grad·gradv_p., right) derivatives of P-waves mean velocity along the profile of A-A1 and B-B1 within Ukrainian Shield.*

Conclusions. We detected a number of new seismic boundaries within the upper mantle ranging from 100 up to 700 km. At present, we are not ready to provide geological conclusions regarding the observed mantle heterogeneities. A number of questions, in particular, what is nature of velocity changes (by changes in lithological composition or phase transitions of minerals), what is the role of pressure and temperature, or whether their change with depth is constant, require further comprehensive analysis of geophysical fields and their transformants. To clarify the mechanism of convection of matter in the mantle, it is necessary to take into account the detailed density distribution and gravity changes. The problem is compounded by the fact that the transverse waves cannot be applied for the reasons above. However, even if you create such a model, it will be significantly *different* in scale from the model built on the arrival of *P*-waves.

References

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